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POWER OUTPUT OPTIMIZATION OF HORIZONTAL AXIS WIND TURBINE USING TAGUCHI METHOD

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A B S T R A C T

The robust design of horizontal axis wind turbine using Taguchi method with orthogonal array is presented in this paper. Taguchi method is a powerful method for optimization of process, quality and performance output. The procedure eliminates the need for repeated experimentation. The approach based on Taguchi method, the signal-to-noise(S/N) ratio, and analysis of variance (ANOVA) are employed to study the performance characteristics. In this paper, the power parameters such as pitch(deg), chord length(m), rotor radius(m) and twist angle(deg). A python code is written to automate the process.

Keywords*: wind turbines, robust design, Taguchi method, ANOVA, S/N ratio.*

1. INTRODUCTION

In the recent years, there is a large requirement of electric power globally. Fossil fuels are not only non-renewable, but also causing a lot of environmental degradation. Due to uneven heating of the earth's surface, wind is generated. The earth receives 1.74 x 1017 watts of power (per hour) from the sun. This kinetic energy of the wind can be utilized for power generation. Horizontal axis wind turbines are preferred for their higher efficiency. Wind energy production shows a wide range of variation due to climatic and technical factors. Experiments were conducted to maximize the power output of an existing setup. Taguchi method of optimization was used to optimize the power output. This process was automated using a python code. Martin, K, et al. (2006) The author has optimized the rotor-to-generator size to maximize the annual energy output under specified wind and budget constraints.

Thumthae, et al. (2009) The author has used both numerical simulation and experimental methods to find different optimum pitch angles of untwisted blades of horizontal axis wind turbine under different wind velocities. Lanzafame, et al. (2009) The author has maximized the annual energy production by optimizing the twist angle of wind turbine blade.Yi Hu, et al. (2011) The author has considered the aspects of robust design including parameter and tolerance design. It presents a methodology to consider multiple design parameters and their tolerances, multiple objectives as well as practical constrains for the robust design of HAWTs using the Taguchi optimization method and its extensions. Ku et al. (1998) The author extended the Taguchi method to handle both positive and negative objective function values in engineering optimization problems in the presence of both single and multiple. Lu et al. (2003) The author successfully improved the quality of solar water heater products by using Taguchi method to find a set of optimum manufacturing factors.Chiang et al. (2005) The author used the Taguchi method and ANOVA for designing the heat sink module and wind capacity of a fan for computer CPUs.

2. METHODOLOGY

2.1 Extractable power from wind turbine

A wind turbine is a device which converts kinetic energy of the wind to usable electrical energy. The extractable power from wind depends on three factors- the velocity of wind(v), density of air (ρ) and swept area. The Cp value varies and depends upon the physical condition, type of blade used and its tip speed ratio. The value of Cp is 59% which is known as Betz limit.

$$\mathbf{P} = C_p * \frac{1}{2} * \rho * \mathbf{A} * v^3$$

Where, A = swept area (area covered by its rotating blade) in m2 .

ρ= Density of the air in kg/m^3

V = Velocity of the air flow in m/s.

C_p= Coefficient of performance

2.2 Data analysis

Data collected from Taguchi/Orthogonal Array (OA) experiments can be analysed using response graph method or Analysis of Variance (ANOVA)

The response graph method is very easy to understand and apply. This method requires no statistical knowledge. For practical/industrial applications, this method may be sufficient.

Analysis of variance (ANOVA) method accounts the variation from all sources including error term. If error sum of squares is large compared to the control factors in the experiment, ANOVA together with percent contribution indicate that the selection of optimum condition may not be useful. Also for statistically validating the results, ANOVA is required.

By conducting the experiment, we obtain the response (output) from each experiment. The response obtained from all the trials of an experiment is termed as data. The data can be either attribute or variable. We know that variable data is obtained by measuring the response with an appropriate measurement system. Suppose in an OA experiment we have only the main factors and the response is a variable.

There are three commonly used S/N ratios—smaller-the-better, larger-the-better, and nominal the-better. We are using the condition larger the better for maximum power output

$$\frac{S}{N} = -10\log_{10}\left\{\frac{1}{n}\left[\sum_{i=1}^{n}\left(\frac{1}{y_i}\right)^2\right]\right\}$$

2.3 Experimental Setup

There are three units in this system viz. wind generating unit, Wind turbine and control unit. Wind generating unit consists of an induction motor with a fan hub sub unit and Variable frequency drive (VFD). This unit will generate different wind speed with the change in frequency of motor input supply (with the help of VFD). This unit consists of a fan (of 7 blades) which generates the wind for turbine movement. Wind turbine unit consists of three rotor blades fixed on the hub and a small PMSG generator. This unit will generate 3 phase electrical power of variable frequency. Control unit consists of different meters viz. voltmeters, ammeters, power analyzers, tachometer and anemometer. This unit also consists of charge controller, battery and inverter. This unit can measure voltages, currents, wind speed, rpm and other power parameters at the different branches of system.

Wind generating unit and wind turbine are placed in an enclosure and fix onto the pillars. These pillars are fixed with the base of enclosure. Anemometer and tachometer sensors are placed near the turbine for measuring the wind speed and rotor RPM. Control unit can be attached and detached from the turbine unit as it is connected with the turbine components (generator) with the help of banana connectors. This control unit can be moved here and there as it is having wheels.

2.4 Optimization of power output using Taguchi

Using orthogonal arrays (OA), Taguchi is a strategy to minimize the number of experiments. Engineers at industries apply the Taguchi method for various applications involving developing new products, monitoring, controlling, and improving the existing product quality and processes. Design of Experiments (DOE) is an efficient technique that requires lesser experimental trials and estimates individual and interaction factors.

Table-1. Input parameters and levels

Control Factor	**Levels**	**A**	**B**	**C**	**D**	**Total sum of all Levels**
Sum Of Factor Level (SFL)	**1**	100.74	240.35	384.12	438.31	1102.46
	2	277.66	371.77	410.31	302.87	
	3	724.22	490.5	308.19	360.84	
Sum of Square of Deviation (SSD)		6194 43.83	939 43.05	168 79.77	2770 6.115	75797 72.765

Percentage Contribution Ratio	81.728	12.393	2.2269	3.655	100
Optimum Level	A_3	B_3	C_2	D_1	
Optimum Values	724.22	490.5	410.31	438.31	

2.5 Implementation of Python

The implementation of Taguchi optimization is done through Python code power output optimization. To increase computational efficiency and to take care the non-linearities, the Python code is used. The python code provides efficient platform from which further extensions are easily possible. As the program code is in modular construction new functions and variables cab built in easily. Through this various other algorithm can also be implemented. The code is structured to compute signal to noise ratio, to build up orthogonal array and from that to develop sum at factor level (SFL) table and finally to obtain parameter wise optimum levels. The SFL table is further utilized to get the graph of Pareto analysis of variance of surface roughness as shown using mat plot library. The important modules of python implementation are as shown below.

```
sfl_abcd = []

def sfl(*sr_snr): import string

import math

import numpy as np

sr_sn = []

def sn_ratio():

 for n in sr_response:

res1 = (1 / (n * n))

       res2 = math.log10(res1)

       res3 = -10 * res2

       sr_sn.append(round(res3,2))

   print(sr_sn)

sr_response = [20.5,27.69,52.5,62.18,97.97,117.51,157.61,246.11,320.44]

sn_ratio()



sr_a = np.array([[1,1,1],[20.5, 27.69,52.55],[2,2,2],[62.18,97.97,117.51],

         [3,3,3],[157.67,246.11,320.44]])

sr_b = np.array([[1,1,1],[20.50, 62.18,157.67],[2,2,2],[27.69,97.97,246.11],

         [3,3,3],[52.55,117.51,320.44]])

sr_c = np.array([[1,1,1],[20.5, 117.51,246.11],[2,2,2],[27.69,62.18,320.44],
```

```
           [3,3,3],[52.55,97.97,157.67]])

sr_d = np.array ([[1,1,1],[20.5, 97.97,320.44],[2,2,2],[27.69,117.51,157.67],

           [3,3,3],[52.55,62.18,246.11]])


    total_1 = total_2 = total_3 = 0

    for i in range(0,6):

        for j in range(0,3):

            if sr_snr[i][j] == 1:

                total_1 += sr_snr[i+1][j]

            elif sr_snr[i][j] == 2:

                total_2 += sr_snr[i+1][j]

            elif sr_snr[i][j] == 3:

                total_3 += sr_snr[i+1][j]


    sfl_abcd.append(round(total_1,2))

    sfl_abcd.append(round(total_2,2))

    sfl_abcd.append(round(total_3,2))


sr_snr = sr_a

sfl(*sr_snr)

sr_snr = sr_b

sfl(*sr_snr)

sr_snr = sr_c

sfl(*sr_snr)

sr_snr = sr_d

sfl(*sr_snr)

print(sfl_abcd)


def divide_chunks(l, n):
```

```
    # looping till length l
    for i in range(0, len(l), n):
        yield l[i:i + 3]
sfl_abcd = list(divide_chunks(sfl_abcd, 3))
print(sfl_abcd)

#find max in list of lists factor wise
optimum_f_l = list(map(max,sfl_abcd))
print(optimum_f_l)

# Sum of squares of deviation
m = sfl_abcd
t_ssd = []
ssd1 = ssd2 = ssd3 = 0
def ssdiff(i):
    for list in m:
        ssd1 = (m[i][0] - m[i][1]) ** 2
        ssd2 = (m[i][0] - m[i][2]) ** 2
        ssd3 = (m[i][1] - m[i][2]) ** 2
    ssd = ssd1 + ssd2 + ssd3
    t_ssd.append(round(ssd,2))

ssdiff(0)
ssdiff(1)
ssdiff(2)
ssdiff(3)

#To find percentage contribution ratio
sum_t_ssd = sum(t_ssd)
```

```
print(sum_t_ssd)

p_c_ratio = []


def percent_cont_ratio():

    for i in range(len(t_ssd)):

        p_c_ratio.append(round((t_ssd[i]/sum_t_ssd)*100,2))


percent_cont_ratio()
```

S/N Curve

```
#To draw sbubplot

#Pareto Analysis of variance:S/N ratio

import matplotlib.pyplot as plt

import numpy as np

x = [1,2,3]

a = [100.74, 277.66, 724.22]

b = [240.35, 371.77, 490.5]

c = [384.12, 410.31, 308.19]

d = [438.31, 302.87, 360.84]

#plot 1:

plt.subplot(1, 4 , 1)

plt.plot(x,a)

plt.xlabel("A Levels")

plt.ylabel("Mean of S/N ratios")

#plot 2:

plt.subplot(1, 4 , 2)

plt.plot(x,b)

plt.xlabel("B Levels")

plt.title("Main effect plot for surface roughness")
```

```
#plot 3:

plt.subplot(1, 4, 3)

plt.plot(x,c)

plt.xlabel("C Levels")

#plot 4;

plt.subplot(1, 4, 4)

plt.plot(x,d)

plt.xlabel("D Levels")

plt.show()
```

3. CONCLUSION

The conclusions drawn from the present work are as follows:

Using ANOVA, the characteristic optimization is being found out for four parameters for the wind turbine. The twist angle has the most contribution to power output. The optimum twist angle is 16 deg, rotational speed is 175 m/s, pitch is 3m and blade chord length is 0.5m.

The outputs have been verified in the python code

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